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Surface Roughness Control Based on Digital Copy Milling Concept to Achieve Autonomous Milling Operation

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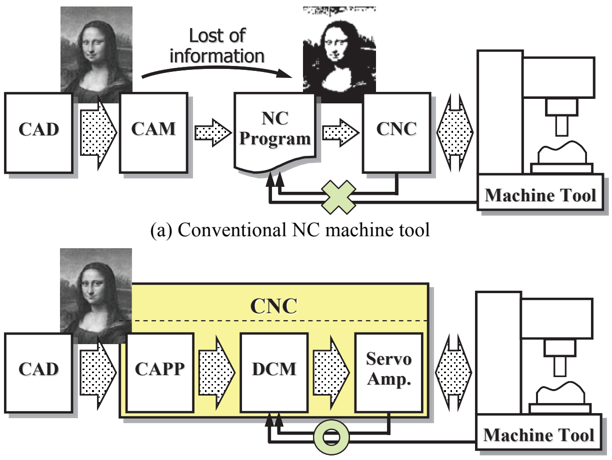
Abstract

In order to develop an autonomous and intelligent machine tool, a system named Digital Copy Milling (DCM) was developed in our previous studies. The DCM generates tool paths in real time based on the principle of copy milling. In the DCM, the cutting tool is controlled dynamically to follow the surface of CAD model corresponding to the machined shape without any NC program. In this study, surface roughness control of finished surface is performed as an enhanced function of DCM. From rough-cut to semi-finish-cut and finish-cut operations, the DCM selects cutting conditions and generates tool paths dynamically to satisfy instructed surface roughness Ra. The experimental verification was performed successfully.

Keywords: Digital Copy Milling (DCM); Machine Tool Control; Surface Roughness Control; Autonomous Machining, Finishing.

1. Introduction

NC machine tools have been widely used to achieve unmanned machining with high quality and productivity. However, NC programs, which are needed for unmanned operation of NC machine tools, require huge amount of time and effort of CAM operators to generate NC programs. Additionally, advanced machining operations utilizing multi-axis or multi-tasking machine tool requires much more time and effort of machining operators. However, number of skilful CAM and machining operators is decreasing in the aging society. Therefore, an autonomous & intelligent machine tool, which can realize easy operations for both CAM and machining operators, is needed. In order to satisfy these requirements, a new concept is indispensable for autonomous and intelligent milling operation achieved by a machine tool itself. Figure 1 shows our proposed concept of an autonomous & intelligent NC machine tool comparing with a conventional NC machine tool.



(a) Conventional NC machine tool

(b) Autonomous & intelligent NC machine tool

Fig.1. New concept to achieve an autonomous & intelligent NC machine tool

A conventional NC machine tool has no function to change instructions or NC commands dynamically

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during machining operation. On the other hand, an autonomous & intelligent NC machine tool has a function of real-time tool path generation, and it is possible to change cutting conditions dynamically for flexible machining process control and cutting trouble avoidance.

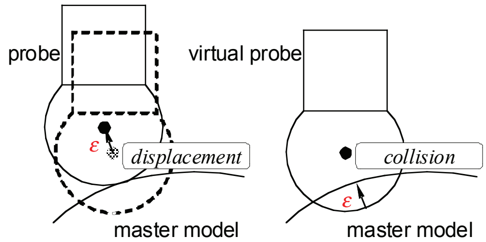
In our previous studies, the new concept named Digital Copy Milling (DCM) was proposed to realize real-time tool path generation for a conventional three-axis NC machine tool. In the experimental milling of sculptured surfaces, not only feed rate but also radial and axial depths of cut can be modified during machining operation [1]. Additionally, the autonomous milling process control using the DCM was realized. In the experimental milling, cutting conditions, even radial and axial depths of cut, can be adapted to keep stable cutting force during machining operation [2]. Furthermore, the tool breakage avoidance was performed successfully using a prototype of autonomous & intelligent NC machine tool controlled by the DCM concept. In the experimental tool crash condition, the cutting tool was retracted safely to avoid tool breakage [3].

2. Digital Copy Milling (DCM)

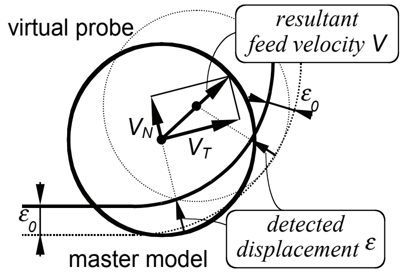
About two decades ago, several tool path generation methods for free form surface were proposed. Some of them generate the curves to drive the milling tool, which intersect the surface by equally spaced parallel planes [4-5]. Alternative methods provide an offset surface to the surface model at a distance equal to the radius of the ball end mill [6-7]. In the reference [7], Bezier and NURBs surface approximations were introduced. These methods aim to generate high quality and precise tool paths, which becomes huge and complicated according to the precision and complexity of machining products. However, these methods did not focus on achieving autonomous and flexible machining operations to change cutting parameters for machining process control and cutting trouble avoidance.

The DCM generates tool paths in real-time to achieve autonomous and flexible machining operations. This is the biggest advantage and difference between DCM and previous tool path generation methods. In order to realize real-time tool path generation, the control principle of copy milling is applied to the DCM.

In the conventional copy milling, the tool motion is controlled to correspond with the motion of tracing probe which is handled manually by a machining operator to follow the master model which has same shape of the product. In the DCM, a 3D CAD model of the product is used instead of the master model for the conventional copy milling. The maximum collision between geometric 3D models of the virtual tracing probe and the virtual master model, which corresponds to the displacement detected by the tracing probe in the conventional copy milling , is detected as shown in Fig. 2(a). And the resultant feed velocity V of tool motion is calculated from the displacement or the collision ε as shown in Fig. 2(b) [1].



(a) Detection of displacement or collision



(b) Feed velocity control

Fig.2. Feed velocity control in the Digital Copy Milling

In order to simplify the tool motion, the scanning line mode for both unilateral and bilateral (or zigzag) paths and the contour line mode are prepared as the basic tool path pattern in the DCM. In the DCM, a machined shape, a material shape, tool properties and cutting parameters are required as the input information of milling operation. Tool paths or CL data are generated in real time, and the milling tool is controlled to follow the motion of the virtual probe as shown in Fig. 3.

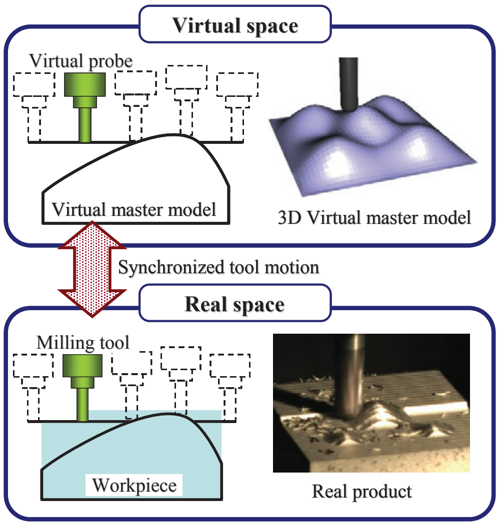


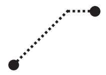
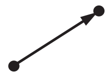
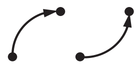
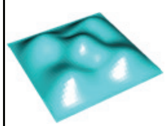
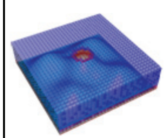
Fig.3. Milling operation performed by DCM

The collision between geometric 3D models of the virtual tracing probe and the virtual master model is detected, the cutting tool is controlled to follow the virtual master model which has the product shape. The DCM can generate tool paths for whole milling operation without any NC program.

3. Voxel Representation of Removal Volume

In conventional NC machine tools, tool motion is instructed by G-code which corresponds to G00, G01, G02, G03 etc. Tool motion is controlled by point for positioning, and by line for contouring. In the DCM, tool motion is controlled by surface. In this study, Voxel representation of removal volume is introduced to enhance the function of the DCM. The volume information which corresponds to the Voxel property is utilized for active tool motion control. It means that the DCM intends to utilize higher level information for tool motion control compared with the conventional G-code as shown in Table 1.

Table 1. Tool motion control in conventional NC machine tool and the Digital Copy Milling.

Conventional tool motion control	Point		Rapid positioning G00
	Line		Linear interpolation G01
			Circular interpolation G02, G03
			Spline interpolation NURBUS interpolation
Tool motion control in DCM	Surface		Digital Copy Milling (DCM)
	Volume		Voxel representation of removal volume & DCM

In this study, the finish surface is represented by a 3D surface model to generate tool paths precisely as same as the previous DCM. In addition, the shape of raw material is represented by Voxels to predict milling situations. The milling situations, such as in cutting or air-cutting motions, in engaging or disengaging motions, tool position from the finish surface, etc. can be predicted by machining shape simulation. Tool motion can be controlled properly according to the milling situation predicted. Furthermore, it is possible to set several codes and values as Voxel properties to utilize for tool motion control. Some codes can be used for changing strategy, and some values can be used for adapting cutting conditions. By utilizing Voxel properties, tool motion control can be handled independently of the tool path generation as shown in Fig. 4.

During the machining process, the DCM generates the tool path precisely using a 3D surface model of the finish surface. On the other hand, the active tool motion control can be achieved by referring the Voxel properties. In some cases, the Voxel properties can be set dynamically according to the results of machining shape simulation. In other cases, the Voxel properties can be set statically according to the machining strategy. In this study, the Voxel properties are utilized for surface roughness control.

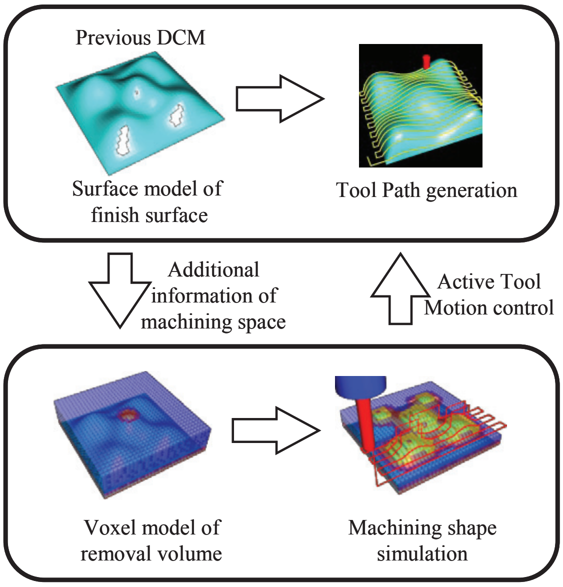


Fig.4. Voxel representation and utilization of Voxel property for tool motion control

4. Voxel Property for Surface Roughness Control

In order to develop an autonomous & intelligent machine tool, surface roughness is an important parameter to achieve both good surface quality and high productivity. In this study, three levels of surface quality of Ra 12.5, Ra 3.2, and Ra 1.6 are considered for surface roughness control.

At first, a VRML format is utilized to import both the machined shape and the surface roughness information to the DCM. A VRML format consists of coordinates of triangle mesh vertexes and surface color of a 3D CAD model. So, surface quality is represented by different surface color corresponding to different surface roughness Ra. In this study, red corresponds to Ra 12.5, green corresponds to Ra 3.2, and blue represents Ra 1.6, respectively. Surface roughness Ra is recognized by surface color which is instructed and stored in Voxel properties.

Furthermore, in order to improve surface quality in finish-cutting, following functions are realized.

(1) To avoid zero cutting speed at the tool tip of ball end mill, tool inclination angle is set. Surface quality is improved by milling with more than ±10 degree of lead angle or less than -10 degree of tilt angle [8]. So, in semi-finish-cutting and finish-cutting, -20 degree of lead angle is set to control the tool posture.

(2) To satisfy the surface quality instructed by surface roughness Ra, tool feed speed and amount of pick-feed are selected properly. To select cutting conditions, following three steps are taken.

(i) Theoretical tool feed speed and amount of pick-feed to satisfy surface quality are evaluated from the theoretical surface roughness formula.

(ii) Preliminary experiment of finish-cutting are performed under the conditions which are combination of theoretical tool feed speed and amount of pick-feed, in order to compare the theoretical surface roughness with measured surface roughness.

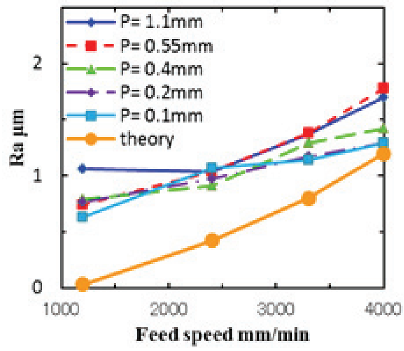
(iii) From the experimental results measured in both the feed and pick-feed direction as shown in Fig. 5, proper cutting conditions of tool feed speed and amount of pick-feed can be selected.

(3) To achieve good surface quality, three steps from rough-cutting, semi-finish-cutting, and finish-cutting operations are performed sequentially. After the rough-cutting operation (see Fig.6 (a)), semi-finish-cutting the surface of Ra 12.5 is performed. Stock allowance of 0.05 mm is left for the surface of Ra 12.5, and stock allowance of 0.15mm is left for other surfaces (see Fig.6 (b)).

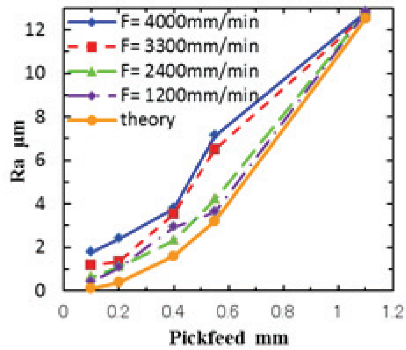
Then, finish-cutting for the surface of Ra 12.5 and semi-finish-cutting for the surface of Ra 3.2 and 1.6 are performed. Stock allowance of 0.05 mm is left for the surfaces of Ra 3.2 and 1.6 (see Fig.6 (c)).

Finally, finish-cutting for the surface of Ra 3.2 (see Fig.6 (d)) and finish-cutting for the surface of Ra 1.6 (see Fig.6 (e)) are performed separately.

(4) To reduce machining time, cutting areas are sectionalized automatically according to the surface roughness Ra instructed. In rough-cutting, semi-finish-cutting, and finish-cutting for the surface of Ra 12.5, the rectangular area which covers all machined surface is recognized as cutting area. In finish-cutting for the surfaces of Ra 3.2 and Ra 1.6, rectangular area which consists of the successive Voxels with same surface roughness of Ra. Figure 7 shows an example of rectangular areas and area number which are recognized and identified automatically by referring Voxel properties. Finish-cutting is performed according to the sectionalized areas one by one.

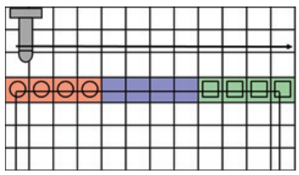


(a) Surface roughness in feed direction

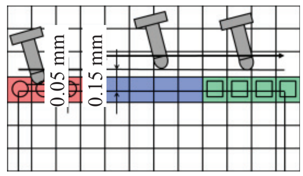


(b) Surface roughness in pick-feed direction

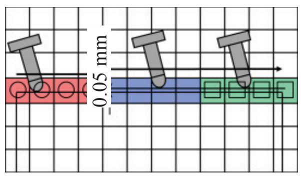
Fig.5. Results of preliminary experiment



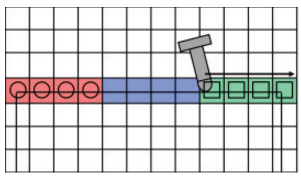
(a) Rough-cutting



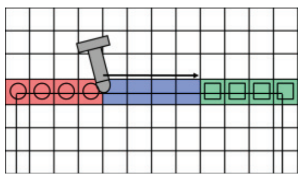
(b) Semi-finish-cutting for the surface of Ra 12.5



(c) Finish-cutting for the surface of Ra 12.5



(d) Finish-cutting for the surface of Ra 3.2



(e) Finish-cutting for the surface of Ra 1.6

Ra12.5
Ra3.2
Ra1.6

Fig.6. Cutting operations from rough-cutting to semi-finish-cutting, to finish-cutting

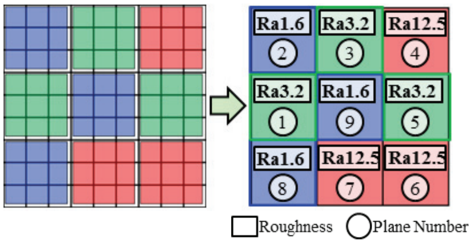


Fig.7. Sectionalized cutting areas and area number

5. Experimental Verification

In order to verify the effectiveness of the proposed concept, which aims to enhance the function of the DCM, cutting experiments have been performed using a vertical 5-axis machining centre NMV1500DCG (MORI SEIKI CO., LTD.). The cutting conditions of this experiment are summarized in Table 2. Cutting conditions for finish-cutting, which are determined automatically according to the Voxel properties or the surface roughness Ra, are summarized in Table 3. In this table, cutting conditions for both the work materials FC250 and A2017P are summarized, respectively. And the DCM generates tool paths autonomously from rough-cutting to semi-finish-cutting, to finish-cutting.

A 3D CAD model using experimental verification is shown in Fig.8. The finished shape and the surface roughness Ra instructed by color represented by a VRML format is delivered to DCM for this cutting experiment.

Table 2. Cutting conditions for rough-cutting

Tool path pattern	Zigzag
Work material	FC250 and A2017P
Cutting tool	Ball end mill (2 flutes)
Tool diameter	6 mm
Radial depth of cut	2 mm
Axial depth of cut	0.5 mm
Rapid feed speed	1500 mm/min
Spindle speed	6000 min^{-1}
Voxel size	2 mm

Table 3. Cutting conditions for finish-cuttign

		Feed speed	Pickfeed
FC250	Ra 12.5	4000 mm/min	1.0 mm
	Ra 3.2	4000 mm/min	0.2 mm
	Ra 1.6	3000 mm/min	0.1 mm
A2017P	Ra 12.5	4000 mm/min	1.0 mm
	Ra 3.2	3000 mm/min	0.3 mm
	Ra 1.6	2000 mm/min	0.2 mm

Figure 9 shows appearance of cutting experiment in which FC250 is being machined. In this experiment, the workpiece was tilted to avoid zero speed cutting at the tool tip. Cutting operations from rough-cutting to semi-finish-cutting to finish-cutting were performed sequentially according to the strategy mentioned in the section 4. Also, the cutting areas were sectionalized certainly, and the stock allowance for semi-finish-cutting and finish-cutting are reserved properly.

The surface roughness control for selecting the tool feed speed and the amount of pick-feed for both for both the work materials FC250 and A2017P was performed successfully. Figure 10 shows the finished surface of FC250 generated by this cutting experiment. Finished surface roughness is measured for all areas of different surface roughness Ra in both tool feed and pick-feed directions.

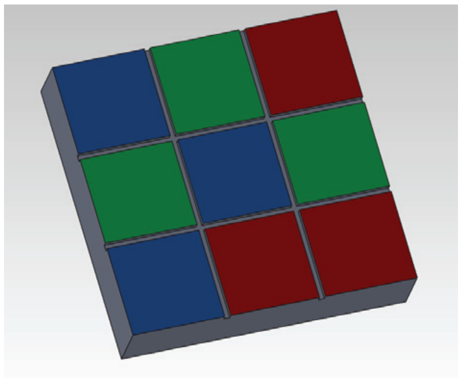


Fig.8. 3D CAD model using experimental verification

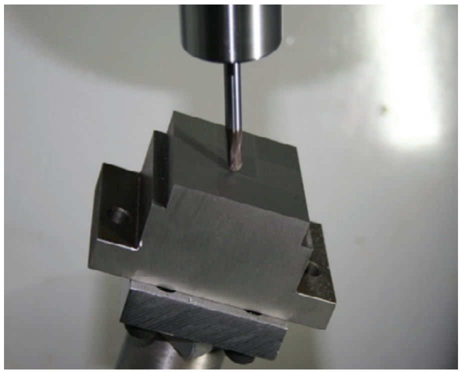


Fig.9. Cutting experiment (Material : FC250)

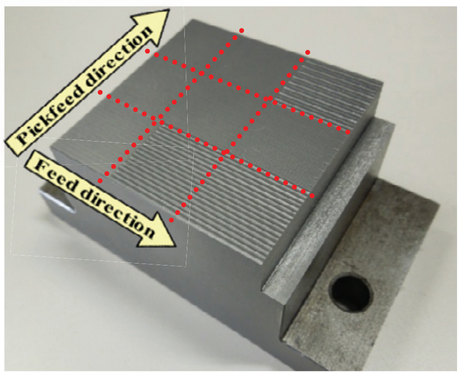
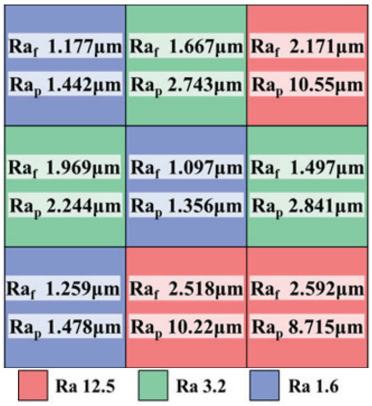
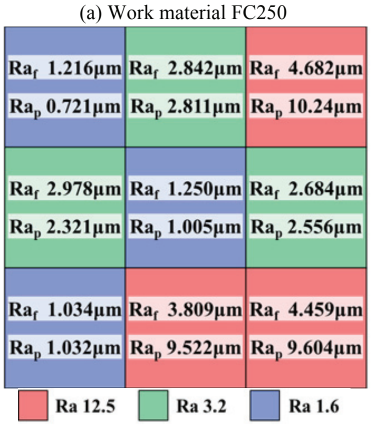


Fig.10. Finished surface of cutting experiment (Material : FC250)

Figure 11 shows measured surface roughness of all areas instructed by the different surface roughness Ra. The results of the work materials FC250 and A2017P are shown in Fig.11 (a) and Fig.11 (b), respectivery. In Fig.11, values of Raf and Rap correspond to the surface roughness Ra along feed direction and pick-feed direction, respectively. All measured surface roughness is less than the surface roughness Ra instructed by the 3D CAD model. These results show that the surface roughness control can be performed successfully under the proposed concept.



(a) Work material FC250



(b) Work material A2017P

Fig.11. Results of measured surface roughness

6. Conclusions

Voxel representation of removal volume is introduced to enhance the function of the Digital Copy Milling system. In this study, the surface roughness control of finished surface can be realized. A VRML format is utilized to instruct both the machined shape and the surface roughness information to the DCM. The experimental verification was performed successfully. The DCM performed from rough-cutting to semi-finish-cutting, to finish-cutting automatically by referring the surface roughness Ra instructed by a 3D CAD model. All measured surface roughness is less than the surface roughness Ra instructed.

7. Future Development

In this study, the surface roughness control was performed as the new function of an autonomous & intelligent machine tool. However, the process plan for whole machining is not considered and only one tool and one tool path pattern is applied from rough-cutting to semi-finish-cutting, to finish-cutting.

For the next step, the strategy to consider the process plan for whole machining is required to select the most suitable cutting tool and tool path pattern automatically. Also, the usage of different cutting tool and the change of spindle speed for semi-finish-cutting or finish-cutting are required to achieve high surface quality and productivity.

Furthermore, a feedback mechanism to update cutting conditions of semi-finish-cutting and finish-cutting operations is needed for keeping the surface roughness Ra under the highest productivity.

Acknowledgement

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